THE USE OF REMOTE SENSING AND GIS IN THE SUSTAINABLE MANAGEMENT OF TROPICAL COASTAL ECOSYSTEMS

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Abstract. The sustainable use and management of important tropical coastal ecosystems (mangrove forests, seagrass beds and coral reefs) cannot be done without understanding the direct and indirect impacts of man. The ecosystem's resilience and recovery capacity following such impacts must be determined. The efficacy of mitigation measures must also be considered. Remote sensing and geographic information systems (GIS) are excellent tools to use in such studies. This paper reviews the state of the art and application of these tools in tropical coastal zones, and illustrates their relevance in sustainable development. It highlights a selected number of remote sensing case-studies on land cover patterns, population structure and dynamics, and stand characteristics from South-East Asia, Africa and South-America, with a particular emphasis on mangroves. It further shows how remote sensing technology and other scientific tools can be integrated in long-term studies, both retrospective and predictive, in order to anticipate degradation and to take mitigating measures at an early stage. The paper also highlights the guidelines for sustainable management that can result from remote sensing and GIS studies, and identifies existent gaps and research priorities.

There is a need for more comprehensive approaches that deal with new remote sensing technologies and analysis in a GIS-environment, and that integrate findings collected over longer periods with the aim of prediction. It is also imperative to collect and integrate data from different disciplines. These are essential in the spirit of sustainable development and management, particularly in developing countries, which are often more vulnerable to environmental degradation.

Key words: biocomplexity, coral reef, human ecology, mangrove, seagrass, spatial resolution, spectral resolution, temporal resolution.

1. Introduction

1.1. Mangrove forests, seagrass beds and coral reefs

Tropical coastal ecosystems include mangrove forests, seagrass beds and coral reefs. Each of these habitats is formed by species that are to a large extent adapted to tropical intertidal or marine life (Table I). Mangrove forests are tropical or subtropical intertidal forests that are composed of halotolerant plant species. They are often located in the muddy, anoxic soils of estuaries, lagoons and river deltas, where their complex of aerial roots provide support and gas exchange, and their viviparous propagules confer an ability either to quickly establish under the parental tree, or to float away and colonise new areas. Seaward, in the infralittoral zone, seagrass

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TABLE I. Comparative generalised table of the properties or environmental requirements that the species forming mangrove forests, seagrass beds and coral reefs commonly possess for existence. It must however be emphasised that not all requirements are necessarily a feature of all species. Detailed descriptions of the advantages of each of these features is considered beyond the scope of this paper.

Requirements	Mangrove forests	Seagrass beds	Coral reefs
Adaptation to saline medium	Salt excretion Salt exclusion Leaf succulence Viviparous propagules	Photorespiration Biocomplexity (relationships with N-fixating bacteria)	Fully adapted organisms of marine nature
Ability to grow submerged, in part or totally	Aerial roots (root submersion)	High surface-to-volume ratios of internal aerenchyma, lacunae and blades	Fully adapted organisms of marine nature
Ability to withstand hydrological action (of marine, riverine or weather origin)	Protected* location Gentle intertidal slope Aerial roots Viviparous propagules	Longitudinal sclerenchyma fibres in rhizomes Gregarious growth	Protected* location Calcareous exoskeleton
Ability to cover distances over water	Hydrochory	Hydrogamy	Pelagic larvae
Adaptation to a certain temperature range	(sub)Tropical distribution	(sub)Tropical distribution Temperate distribution	(sub)Tropical distribution

*Mangrove forests are protected against wave or storm action and tidal currents by small islands and coral reefs in front of the coast, whereas coral reefs are protected against riverine sedimentation by mangrove forests, the root complex of which slows down the river flow.

beds may lie alongside the mangrove. Seagrasses are marine flowering plants that are often anchored in the sandy substrate. They are able to complete their life cycle in a saline environment, while completely immersed. Like the root complex of mangroves, seagrasses also stabilise the substrate. Coral reefs, located seaward again, rank among the most biologically productive and diverse of natural ecosystems. In contrast to the habitat-building species in mangroves and seagrasses, true reef-building corals are marine animals (Anthozoa polyps) that collectively deposit calcium carbonate to build a colonial structure that provides a habitat for a vast array of other organisms.

Mangroves and coral reefs occur mainly between the Tropics of Cancer and Capricorn, extending further north and south only where there are warm currents. Their surface is estimated at about 181,000 sq km (Spalding et al., 1997), and between 300,000 and 600,000 sq km, respectively, and they are found in the waters of over 100 countries (Bryant et al., 1998). Seagrasses, being represented by both temperate and tropical species, have a larger geographical distribution, but the exact surface is unknown.

Coral reefs are undoubtedly one of the major biodiversity hot spots on our planet with at least 4,000 species of fish and 800 species of reef building coral (*loc. cit.*), not to mention other organisms like molluscs, crustaceans or echinoderms. Mangrove and seagrass ecosystems are rather poor in the plant species that actually constitute the habitat – <70 species globally and <50 locally for mangroves

(Spalding et al., 1997), and <50 species globally and <12 locally for seagrasses (Duarte, 2000). However, the number of species they hold and the ecosystem services they offer are manifold (e.g. Coppejans et al., 1992; Bandaranayake, 1998; Nagelkerken et al., 2000; Duarte, 2000; De Troch et al., 2001). Seagrass biota, for instance, can be subdivided in leaf biota (epiphytes including their micro- and meiofauna, sessile and mobile epifauna), stem and rhizome biota, a variety of benthos and finally, sedentary and migratory mobile fauna foraging under the leaf canopy. For each of the above tropical coastal ecosystems a large amount of species can be listed, and new species continue to be discovered each year (e.g. Abdel Wahab et al., 1999; Coppejans et al., 1999; Muthumbi and Vincx, 1999; Samyn et al., 2001; Takeuchi and Hatano, 2001). In addition, biotic and environmental ecological interlinkages within and between mangrove forests, seagrass meadows and coral reefs have been demonstrated (Hemminga et al., 1994; Marguillier et al., 1997; Schrijvers et al., 1997; Bouillon et al., 2000, 2002). More on how the interactions between species and the loss of species within one ecosystem affects the diversity and ecology of other members of the same and adjacent communities remains to be elucidated (Ellison and Farnsworth, 2001).

The large direct and indirect services to man by these ecosystems must be considered. Mangroves and coral reefs protect the coastline against erosion. Seagrasses and mangroves act as breeding, spawning, hatching and nursing grounds for many marine species, of both lagoon and off-shore origin. Some of these species are important from a 'unique biodiversity' point of view, as they migrate between mangroves and coral reefs such as sharks or seahorses (Stafford-Deitsch, 1996), whereas others are socio-economically essential species (Baran, 1999). Among the wood products that mangroves offer are fuelwood, building poles, fishing gear, furniture and small household tools (Stafford-Deitsch, 1996; Dahdouh-Guebas et al., 2000a). Non-wood products range from ointments and food items to fish poison and medicinal products, whereas secondary products can be, for instance, edible fauna or honey from bees, cultivated in the mangrove (*loc. cit.*). In addition, all three ecosystems have a aesthetic value for local inhabitants and visitors.

1.2. Anthropogenic influences on tropical coastal ecosystems

A majority of the world's human population has long been established near water bodies such as lakes, rivers and especially oceans. Eight percent of the total global population, almost half a billion people, live within 100 km of a coral reef (Bryant et al., 1998), and this number increases to 39% for the population living within 100 km of a coastline (Rosen, 2000). The coastal zone in many countries is subjected to ever increasing anthropogenic pressure. Approximately 75% of sheltered tropical coasts worldwide were once occupied by mangroves (Chapman, 1976), but today this figure is said to be reduced to ca. 25%. Published data in fact report that between 5% and nearly 85% of original mangrove extent has been lost, particularly during the second half of the 20th century (Burke et al., 2001). Mangrove destruction occurs as a result of reclamation for village expansion, agriculture, tourism and aquaculture impoundments (Farnsworth and Ellison, 1997), oil spills (Duke et al., 1997; Lamparelli et al., 1997) and freshwater diversion (e.g. Tack and Polk, 1999; Dahdouh-Guebas et al., 2000b). For coral reefs it is reported that they have been damaged or destroyed in more than 93 countries (IUCN, 1993), particularly by coastal development and over-exploitation practices such as tourism, siltation, bottom-net and cyanide fishing, pollution and coral mining (Bryant et al., 1998).

This dramatic degradation necessitates a rational management of ecosystems and resources on a local, regional and global level. This is particularly true for developing countries, a majority of which are (sub)tropical. Within such countries, those areas developing at a high rate are often characterised by competition between economic sectors such as aquaculture, industry and tourism and concern for the environment. This conflict often results in the environment paying the highest price, in certain cases under the influence of political patronage (e.g. Foell et al., 1999). The result is too often a lose–lose situation, in which the economic gain is a short-term one, and neither the environment nor the economic activity survives. High economic losses were reported following reef destruction in Indonesia and the Philippines (Cesar et al., 1997; White et al., 2000), and mangrove destruction in Sri Lanka and Thailand (Jayasinghe and Macintosh, 1993; Sathirathai and Barbier, 2001). With respect to lagoon and offshore fisheries economic losses of 14.4 metric tons of shrimp harvest and nearly €140,000 in revenues are predicted for a marginal decline in mangrove area in Campeche, Mexico (Barbier, 2000). The specific value of tidal marshes and mangroves is estimated at €9,990 per ha and at €1.6 trillion world-wide (Costanza et al., 1997). Each hectare of mangrove is estimated to generate 1.0–11.8 tons of fisheries catch per year in developing countries, with a market value of €900–12,400 (Rönnbäck, 2001).

The developing status of many countries implies that local people are often dependent on the nearby ecosystems (IUCN, 1993; Turner et al., 1996; Cormier-Salem, 1999; Dahdouh-Guebas et al., 2000a). This requires an integrated interdisciplinary approach in order to reach a sustainable equilibrium between the ethnobiological needs (i.e. the needs of indigenous people in their reciprocal interaction with biological organisms in their local environment) and the environmental conservation. This dilemma may also require an *ad hoc* solution, for example, when dealing with a habitat, in which highly endangered species as well as highly dependant traditional communities live. In both cases, both the environment and indigenous people must be protected with ecological criteria being treated at the same level as economical and social ones in decision-making (e.g. trade-off analysis, Brown et al., 2001). Equally important is the evaluation and monitoring of the interdisciplinary or community-based management efforts (e.g. Walters, 1997; White and Vogt, 2000; Westmacott, 2001).

Efforts to popularise these ecosystems for the public, and to emphasise the need for conservation occurs by way of books, articles, public presentations and the

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internet (Stafford-Deitsch, 1996; Bryant et al., 1998; Wyllie-Echeverria, 1998; Cormier-Salem, 2000; Dahdouh-Guebas and Koedam, 2001). However, the sustainable use and management of tropical coastal ecosystems cannot be done without understanding the direct and indirect impacts of man on these ecosystems. It is necessary to foresee the consequences of these impacts by knowing the ecosystem's lag-time, resilience and recovery capacity. Mitigating measures must also be considered.

The study of all of the above aspects in tropical coastal ecosystems requires research with respect to the high spatio-temporal dynamism in land-use and land-cover patterns (marine and coastal changes), in order to assess and predict the extent of anthropogenic impacts or environmental changes. This includes changes in population structure of floral and faunal assemblages, in biodiversity and ecosystem functioning, and in the complexity of their regulation (termed 'biocomplexity'), and in ethnobiological uses. An excellent tool that is increasingly important in the detection, description, quantification and monitoring of those changes is remote sensing, which, in combination with geographic information systems (GIS) and fieldwork, is an effective management tool.

This paper particularly focuses on the applications of remote sensing and GIS to provide various guidelines for the sustainable management of tropical coastal ecosystems, with an emphasis on mangrove forests. It highlights remote sensing case-studies from coastal areas on land-use patterns, environmental disasters, population structure and dynamics, and stand characteristics. It shows how new digital remote sensing technology can be integrated in long-term studies that combine past and present in order to make predictions about the future, and, if necessary, to indicate action to prevent degradation.

2. Remote sensing and GIS as tools

The term 'remote sensing' is broadly defined as the technique(s) for collecting images or other data about an object from measurements made at a distance from the object, and can refer, for instance, to satellite imagery, to aerial photographs or to ocean bathymetry explored from a ship using radar data. However, in the present context, only optical images acquired by space-borne or air-borne sensors are considered.

Over the last few decades remote sensing technology has been used increasingly by the scientific community to describe and monitor a variety of systems on a local or global scale. This technology has evolved from pure visual imagery (e.g. panchromatic aerial photographs) to multi-spectral imagery (e.g. Thematic Mapper). The spatial resolution has improved and reached a level at which the quality of public available space-borne imagery challenges that of air-borne imagery for the first time.

GIS are widely used as tools to digitise remotely sensed or cartographic data complemented with various ground-truth data, which are geocoded using a global positioning system (GPS). GIS can be used to analyse the spatial characteristics of the data over various digital layers. If sequential data are available quantification of spatial changes becomes possible through overlay analysis. GIS is an expanding information technology for creating databases with spatial information, which can be applied to both human settlements (e.g. demographic databases) and to the natural environment (e.g. distribution of populations and environmental factors). Most importantly, the combination of both types of database can ensure sustainable management. GIS will continue to improve as an essential acquisition tool and analysis tool respectively not only in the analytical description of spatial subjects, but also in environmental planning, impact assessment, disaster management and simply monitoring remote sensing.

It is considered beyond the scope of this paper to discuss technical steps involved in remote sensing data acquisition, image processing and modelling. Instead, examples of applications concerned with the natural environment and human coastal settlements experiencing (sustainable) development in tropical countries are considered. The use of remote sensing and GIS in the sustainable management of tropical coastal ecosystems has been discussed in *Environment, Development and Sustainability* (Dahdouh-Guebas, 2002) through various case-studies. These case-studies, as well as other existing literature, will be considered in the context of guidelines for sustainable management and development.

3. Remote sensing and GIS case-studies on tropical coasts

Remote sensing and GIS have been used to study mangrove forests (e.g. Ramachandran et al., 1998), seagrass beds (e.g. Ferguson and Korfmacher, 1997; Dahdouh-Guebas et al., 1999; Pasqualini, 2001) and coral reefs (e.g. Holden and Ledrew, 1999; Lubin et al., 2001). Blasco et al. (1998) reviewed the suitability of various remote sensing technologies in different mangrove research fields and concluded that aerial photography is best suited for investigating the density, phenology, hydrological status, human impact, height and floristics of mangrove forests. Despite innovations in remote sensing technology, aerial photographs often remain as the preferred technology (Ramsey and Laine, 1997; Dahdouh-Guebas et al., 1999; Kadmon and Harari-Kremer, 1999; Mumby et al., 1999; Dahdouh-Guebas et al., 2000b; Hyyppä et al., 2000; Manson, 2001; Chauvaud et al., 2001; Lubin et al., 2001; Verheyden et al., 2002; Sulong et al., 2002). Also in the study of larger mangrove assemblages, data with a high spatial resolution may reveal relevant details on vegetation structure dynamics (Dahdouh-Guebas et al., 2000b). Such results may be used to predict future changes in vegetation structure (Dahdouh-Guebas, 2001).

Yet, many papers seem to rely primarily on the quality of 'spatial resolution', in which case the above evaluation is true to a large degree. In fact, three basic qualities inherent to remote sensing data must be recognised: 'spatial resolution', 'temporal resolution' and 'spectral resolution'. These can be summarised in the axes of a three-dimensional graph, and the requirements of different research topics with respect to these resolutions can then be plotted (Figure 1a), as well as the specifications of available remote sensing sources (Figure 1b). The following case-studies illustrate the resolution features that remote sensing data in their respective research fields (Figure 1a) can or must possess.

3.1. Monitoring land-cover patterns and disasters

The identification of land-use or land-cover patterns is usually done on a medium or large spatial scale and does not require remote sensing data with a high spatial resolution. However, aerial photography may be used as it is often the only remote sensing source available (physically or financially) in many tropical countries (e.g. Dahdouh-Guebas et al., 2002b; Sulong et al., 2002; Verheyden et al., 2002). The interpretation of aerial photography must however be carried out rigorously and described accordingly. Sulong et al. (2002) takes satisfaction with an interpretation key based on 'tone' and 'texture', without defining these terms, and qualifies them using descriptions such as 'dark', 'darker', 'coarse' or 'coarser'. Not only is verbally no information contained in such a description, it is also not repeatable considering the 'subjective' researcher-dependent nature inherent to aerial photography interpretation. Even though the authors probably carried out a consistent analysis and the results are indicative for a need for conservation, aerial photography interpretation remains extraordinarily difficult in diverse environments such as tropical coastal ecosystems, and analyses must be supported with useful attributes that can be understood by other research groups. Verheyden et al. (2002) combined the well defined 'tonality', 'texture' and 'structure', attributes that can additionally be combined with 'shape', 'shade' and 'position' of the trees, all of which reveal a small piece of the identity of a mangrove tree species. Integrated in a more complex identification key, the combination of all these image attributes may reduce the ambiguity to a minimum.

The spectral resolution depends on the study topic, but usually does not require more than a distinction of vegetated and agricultural areas amongst others, which can be done using infrared wavelengths (IR). The temporal resolution depends on whether the study is momentary or aims at monitoring the changes in land-cover over time. The highest temporal resolution of 1 per day, in combination with high spatial and spectral resolutions, may be required to continuously monitor catastrophic phenomena such as volcanic eruptions, oil pollution, forest fires, weather events and even nuclear disasters (e.g. Rycroft, 2000; San Miguel Ayanz et al., 2000; Flynn et al., 2001; Venkatachary et al., 2001). Lower temporal resolutions serve the study of 'before–after'-effects. De La Ville et al. (2002) for instance illustrates how the recent IKONOS satellite imagery may prove itself as a tool in reconstructive urban planning.

Based on this type of remote sensing, it is possible to provide management guidelines for immediate action (Altan et al., 2001), or to construct a long-term management strategy to mitigate human impacts. For instance, in ecological footprint

	Spatial	Temporal	Spectral	
1	>1km	1/decade	Panchromatic	1
2	100m-1km	1/year	RGB	2
3	50m-99m	1/month	+ near-IR	3
4	10m-49m	1/week	+ far IR	4
5	<10m	1/day	+ thermal IR	5

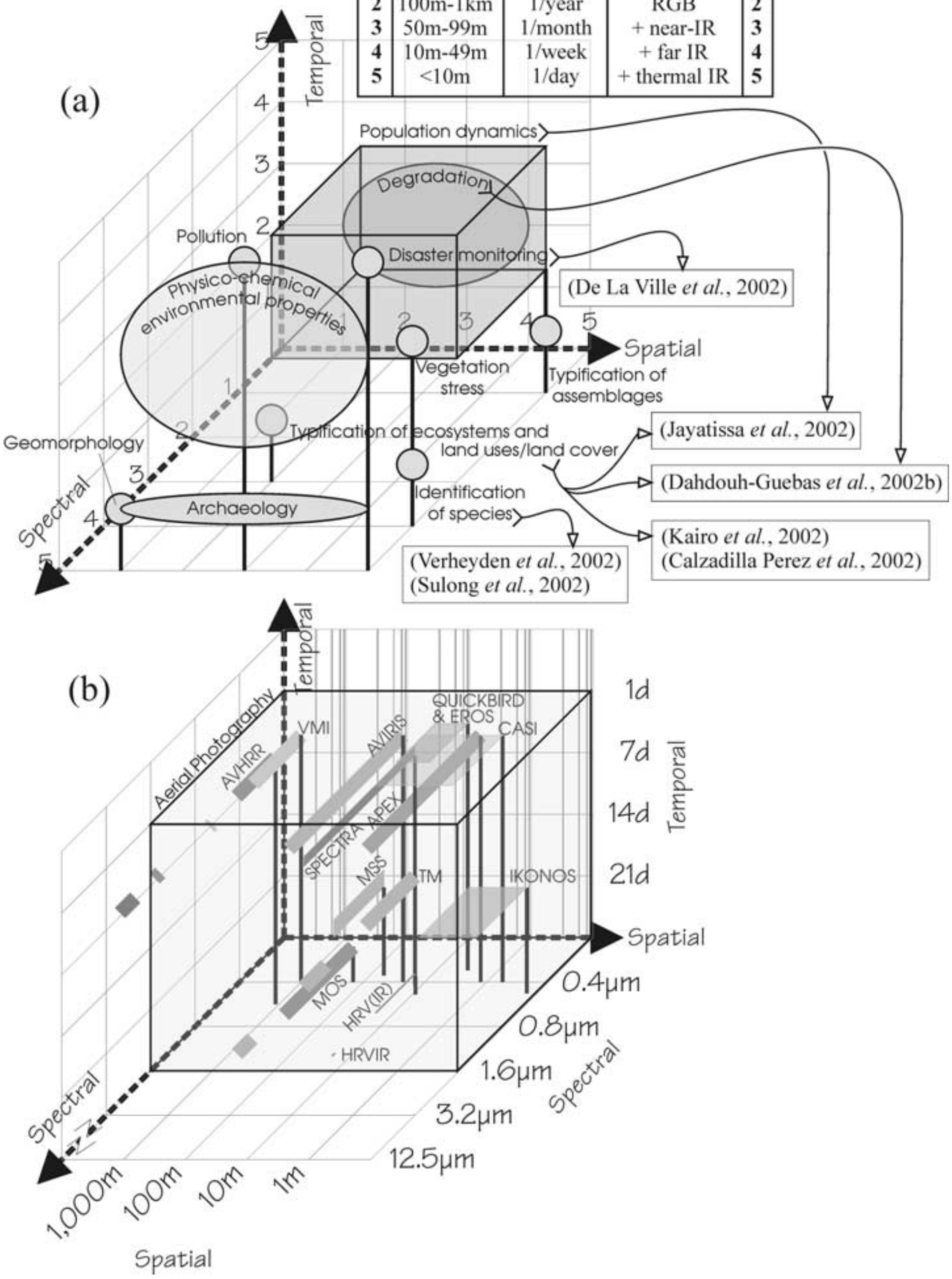

Figure 1. Requirements of different research fields/topics (a), and specifications of some common and new optical remote sensing sources (b), with respect to spatial, temporal and spectral resolution. Each of these resolutions has been categorised according to the scale above the graph (a), or has been given as a quality gradient from low to high (b). Arrows illustrate where the case-studies selected from *Environment, Development and Sustainability*'s special issue on 'Remote sensing and GIS in the sustainable management of

analysis, the surface ratio between a human impact area and the supporting natural resources area can be calculated in order to advise local authorities on sustainability issues, often a delicate industrial development *versus* nature conservation matter (e.g. Dahdouh-Guebas et al., 2002b). Another example of longer term monitoring based on remote sensing and GIS is the management of disease outbreaks that may affect a significant number of individuals after the first effects of a disaster have passed (Guptill, 2001). This is an application that gains importance in large coastal cities and on small islands.

3.2. Monitoring population structure

The study of vegetation structure in mangrove forests and seagrass beds can focus on single genera, associations and zonation in the vegetation (Dahdouh-Guebas et al., 1999; Dahdouh-Guebas, 2001; Verheyden et al., 2002; Sulong et al., 2002), or on its temporal dynamics (e.g. Sargent et al., 1995; Dahdouh-Guebas et al., 2000b; Jayatissa et al., 2002; Calzadilla Pérez et al., 2002). The same type of study can also be applied to cyanobacterial, algal or diatom populations that are for instance known to bloom around coral reefs in coastal waters (e.g. Signorini et al., 1999), and even animal populations may be included in the analysis in a GIS environment through GPS-coded locations. The spatial and spectral resolution for the study of population structures may vary over the range given in Figure 1 depending on the scope of the study, whereas temporal resolution is usually low in the light of the relatively slow nature of vegetation change, whether or not anthropogenically induced.

Management guidelines may vary from pinpointed causes of change and actions to be taken with respect to anthropogenic influences, to simulations and predictions based on vegetation history.

3.3. Monitoring stand characteristics

Whereas the temporal resolution depends again on the specific scope of the study, the monitoring of specific stand characteristics may require a high spatial and spectral resolution. On one hand, the distribution of trees in a forest requires separate crowns to be visible in order to estimate for instance biomass (e.g. Holmgren et al., 1997; Kairo, 2001; Kairo et al., 2002). High spectral qualities on the other hand, may allow the assessment of the health of individual trees through their photosynthetic or water relation properties (e.g. Narayanan and Pflum, 1999; Ceccato et al., 2001).

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tropical coastal ecosystems' (Dahdouh-Guebas, 2002) in part fit into the graph. The 'spectral range' of aerial photography must be understood as a sole image with grey values of panchromatic (= visible Red-Green-Blue or RGB) or infra-red (IR) origin, rather than as separate superimposable image layers that are commonly available from other sensors. *Sensor abbreviations*: air-borne: APEX = air-borne PRISM experiment; AVIRIS = air-borne visible infrared imaging spectrometer; CASI = compact air-borne spectrographic imager; Space-borne: AVHRR = advanced very high resolution radiometer; HRV = high resolution visible imaging system; HRVIR = high resolution visible and infrared; MOS = modular optoelectronic scanner; MSS = multi-spectral scanner; PRISM = process research by an imaging space mission; SPECTRA = surface processes and ecosystem changes through response analysis; TM = thematic mapper; VMI = vegetation monitoring instrument.

There is a need for more research on the computer-aided delineation of individual trees and other silviculture characteristics in imagery with very high spatial resolution (e.g. Brandtberg and Walter, 1998; Kadmon and Harari-Kremer, 1999). At present, the human eye is still the most powerful and unsurpassed tool to integrate different image attributes such as tonality, texture, structure, shape, shade and position characteristics in order to identify forestry features on very high spatial resolution imagery (Dahdouh-Guebas, 2001).

Assessment or monitoring of detailed characteristics of vegetation stands may result in the needed management guidelines with respect to forest conservation or sustainable (community-based) silviculture. Kairo et al. (2002) mentions that such GIS-digitised stand information is an important tool in the quick retrieval and analysis of forest characteristics. In fact, a GIS, in which data on, for instance, silviculture, forest cutting and human settlements are stored and updated, can be readily manipulated to retrieve how much wood is present and how many scores can be cut where and when. Such data can even be forecasted if allometric relationships for the various mangrove trees species are known. It is such a type of integrated information system that will help in the sustainable management of these ecosystems.

3.4. Monitoring other environmental features and processes

Some aspects have not been elaborated so far, because of their less obvious or non-optical nature in remote sensing, but their existence is worth mentioning here, as some are applicable to coastal habitats. Remotely sensed radar data such as from synthetic aperture radar (SAR) is widely used and provides some advantages over optical imagery, to which it may prove complementary. Radar technology allows penetration through clouds or even through tree canopies to reveal what is underneath (Jordan et al., 1995; Guo, 2000) and is also used in for instance flood monitoring (Guo, 2000).

Another example is the monitoring of physico-chemical environmental properties such as the concentration of certain elements or molecules in the soil or in the atmosphere. One of the best known examples is the monitoring of atmospheric ozone in the light of global change, but sensors such as AVIRIS (Figure 1b) may identify a variety of substances ranging from H_2O, CO_2 and CH_4 to geological mineral mixtures (Green et al., 1998). Future space missions are currently set up to investigate such atmospheric composition, water vapour content, processes and climate interaction in more detail (Battrick and Harris, 2001; Harris and Battrick, 2001).

4. Integration of past, present and future remote sensing studies

The current challenge to remote sensing and GIS-based research is to combine data from the past and present in order to predict the future. On one hand, data from the past that were never ground-truthed require a calibration to current data, preferably (but not always possible), *within* the same remote sensing technology (e.g. Dahdouh-Guebas et al., 2000b; Verheyden et al., 2002). On the other hand it is likely that a long-term or integrative study will combine remote sensing data from different sources. This requires a calibration *between* remote sensing technologies. Discrepancies in post-launch calibrations of certain remote sensing devices may cause artefacts such as surface area change (Gutman, 1999), and so may the shift from one remote sensing source to another (Petit and Lambin, 2001; 2002). However, it is possible to integrate cartographic and multi-source remote sensing data into a homogeneous time series (*loc. cit.*).

It seems that among the available remote sensing technologies producing high spatial resolution data, aerial photography has been superior to space-borne data, despite the higher spectral resolution of the latter. However, digital air-borne multispectral imagery such as the compact air-borne spectrographic imager (CASI) is at least as accurate as aerial photography for the same purpose and it is less expensive to acquire and therefore more cost-effective (Mumby et al., 1997). It is also important to proceed in the evaluation of new scientific applications of more common imaging techniques such as video and photography from low-flying aircrafts (Herwitz et al., 1998; Eleveld et al., 2000). In space-borne remote sensing, the IKONOS satellite, launched in September 1999, was the first one to challenge the very high spatial resolution data obtained from air-borne remote sensing technology (Figure 2). Compared to aerial photography, which may have a spatial resolution as low as 20 cm, and CASI (resolution: 1 m), IKONOS has a spatial resolution of 1 m for panchromatic imagery and 4 m for multi-spectral imagery, and its future successors are reported to generate images with a spatial resolution of approximately 50 cm (Richard and Jia, 1999). The EROS satellite, launched in December 2000, has a spatial resolution of 1.8 m but no multi-spectral capability. However, its future successors are reported to generate multi-spectral imagery combined with a spatial resolution of 0.82 m (Donnio et al., 2001). In the mean time, the QUICKBIRD satellite, launched in October 2001, leads the quality list of optical remote sensing with panchromatic imagery of 70 cm spatial resolution, and multi-spectral imagery of 3 m spatial resolution. Yet, it is not unthinkable that too much spatial detail (particularly if combined with a high spectral resolution) may obscure image analysis, as single image objects such as tree crowns will be characterised by a large array of pixels featuring internal variation, for instance crown side (sun/shade), leaf age (fresh/scenescent), water content, etc. Therefore, it is as important to explore the construction of both manual identification keys and programmed identification algorithms that integrate spectral data (cf. 'tonality' above), 'texture' and 'structure' analysis.

With respect to the spectral resolution, future research should continue to assess the applications of remote sensing sensors. On one hand, this should be done specifically for the identification of a larger range of organisms, on the other hand, it should concentrate on a larger range of wavelengths. Vegetation is easier to study because of its immobility, and, specifically in remote sensing, because of its characteristic reflectance in the infrared wavelengths due to its photosynthetic pigments. However, it remains an under-explored challenge to study animal populations using thermal features or radar tracking from satellite data. Such studies are extremely limited

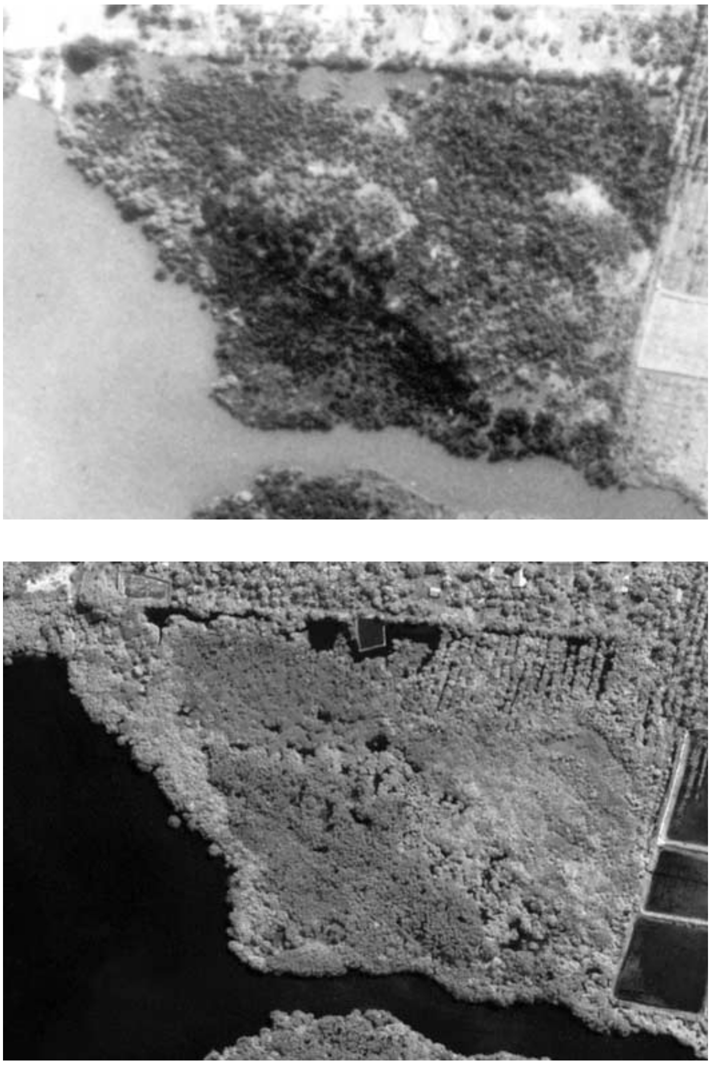

Figure 2. (a) Black and white aerial photograph and (b) panchromatic IKONOS satellite image of a little changed mangrove formation (Pambala, Sri Lanka), to illustrate how vegetation structure features so far available from aerial photography only can now in part be detected from very high (spatial) resolution space-borne imagery. In addition, a 'pansharpenend' multi-spectral image with the same resolution can be produced by, for instance, substituting the 'intensity' component of a true or false colour composite in HIS-format (hue, intensity and saturation) by the panchromatic image shown (b) in order to reveal more spectral details (not shown). Note that water bodies (black), even those below canopy, are more conspicuous in (b) because of their high absorption in the near-infra-red wavelength, which is included in the spectral resolution of the IKONOS satellite (0.45–0.90 μm).

and almost exclusively focused on ornithological navigation as detected from radar data (e.g. Alerstam, 2001). This research field, together with similar entomological studies, is skewed towards ground radar applications (e.g. Capaldi et al., 2000). Yet, the ability of animal populations such as seals to induce temperature changes in the environment (McCafferty et al., 1999) is an indication of the potential of thermal infrared remote sensing, provided sufficient spatial resolution is available. The recent report of the UV absorption compounds in marine protists (Jeffrey et al., 1999) may be indicative for the spectral potential inherent to both existent and new sensors.

The high temporal resolution of space-borne imagery, in contrast with air-borne imagery, marks another milestone in remote sensing technology. IKONOS data has for instance the advantage of a high spatial and a high temporal resolution, a combination that was not common before its launch. Particularly in dynamic ecosystems, this allows for a comprehensive time-series, which can be readily digitised and analysed in a GIS. However, in some cases visual comparison between the information from separate GIS layers, which result from different moments in time, is preferred to overlay analysis. Despite the analytical power of overlay analysis in a GIS, some very high resolution studies, on, for instance, biodiversity, in which the distribution patterns of single species or assemblages may be highly relevant, may generate complicated maps about the temporal changes that are difficult to interpret (Verheyden, 1997).

The main disadvantage of some of the new remote sensing technologies such as IKONOS is their commercial nature, and the very high prices charged are a limiting factor that prevents the scientific community to access these data. This is particularly true for developing countries, the government of which may bear the high cost of aerial surveys, but make the photographs available at a marginal cost to the local academic institutions, far below the price of satellite imagery with the same resolution.

Many publications exist on the effects of global change for marine environments. It is clear that deltaic areas, small islands, coral atolls and coastal wetlands appear to be particularly vulnerable to climatic change (Nicholls et al., 1999; Klein et al., 2001), and that more marine protected areas are needed (e.g. Pernetta, 1993a–c; Pockley, 2000). Apart from the integration of past and present data outlined above, a lot of effort should be put into the prediction of future scenarios and the establishment of early warning systems in order to help guarantee the survival of a sustainable ecosystem. Dahdouh-Guebas (2001) elaborates on how future mangrove vegetation structure and degradation can be predicted based on vegetation history and current vegetation structure in the field, and how remote sensing technology can be combined with multivariate analysis (Dahdouh-Guebas et al., 2002a). For instance, sequential remote sensing with very high spatial resolution can be used to view whether a mangrove forest is dynamic or static and whether or not it has degraded. Interviews with local people may help to understand what are the underlying causes of degradation (Dahdouh-Guebas, 2001) – even to researchers from exact sciences these socio-economic surveys are very important, as they are the only source of retrospective information apart from long-term sequential remote sensing. Figure 3 shows how the three aspects above together generate information about the regeneration capacity of the ecosystem and act as an early warning system. If degradation symptoms appear, human interference such as rehabilitation may be required. It is equally important to evaluate the rehabilitation effort, successional aspects and

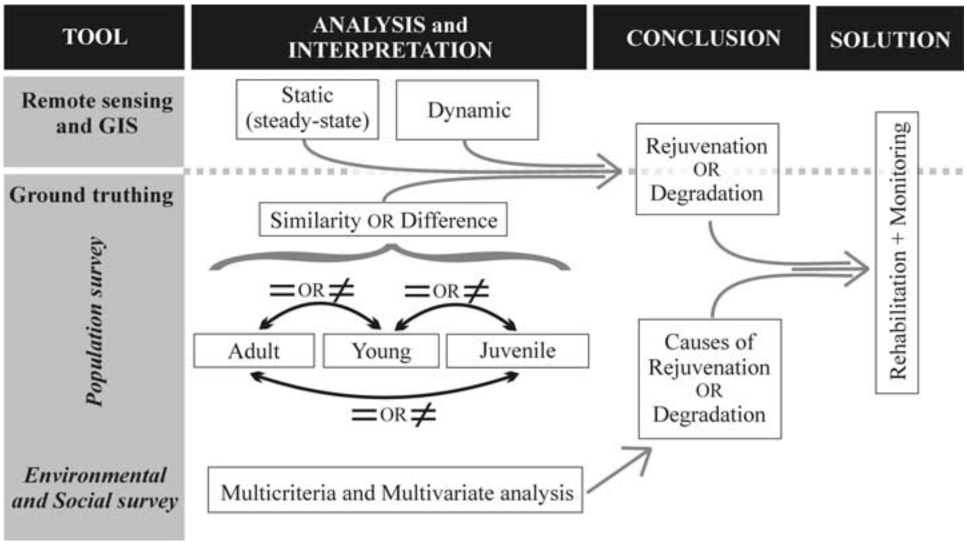

Figure 3. Schematic of the steps involved in an early warning system, a combination of past conditions (multi-source remote sensing and GIS-based), present conditions (based on remote sensing and GIS, biotic populations, environmental factors and human opinions), and future predictions (based on actual similarities between e.g. the distribution of adult, young and juvenile ecosystem elements), in order to anticipate the need for rehabilitation and further monitoring (both in the field and through remote sensing). See text for more details on the application of this scheme to mangrove forests.

biotic migration patterns. Note that a long-term retrospective remote sensing study on the evolution of a given area will undoubtedly confront the researcher with aerial photography, the universality and complementarity of which therefore resists technological innovation (see also Figure 1).

An important challenge to the sustainable management of ecosystems, whether or not tropical and coastal, is the use of GIS in the integration of data originating from ecology, geography, sociology, and other disciplines. For instance, biocomplexity, ethnobiology, demography, sociology and economics, research fields that are not directly associated with the use of remote sensing and GIS, can nonetheless often be integrated into such a spatial database (e.g. Jensen and Cowen, 1999). A GIS-based combination of such fields to understand the biocomplexity of certain systems is not common. However, more applied possibilities such as GIS-based (disaster) management now becomes more and more widespread (e.g. Salvi et al., 1999; Altan et al., 2001; Guptill, 2001; Venkatachary et al., 2001). At the level of organising new satellites for improved remote sensing, an emphasis should be put on international collaboration in order to reduce the cost of the space-borne missions (Bailey et al., 2001).

5. Conclusion

There is a need for more comprehensive approaches that deal with new remote sensing technologies and analysis in a GIS-environment, and that integrate findings collected over longer periods with the aim of prediction. It is also imperative to collect and integrate data from different disciplines. These are essential in the spirit of sustainable development and management, particularly in developing countries. Not only do these countries hold a large part of our planet's biodiversity (particularly from tropical coastal ecosystems), but also they are the most vulnerable to environmental degradation. Calzadilla Pérez et al. (2002), Dahdouh-Guebas et al. (2002b), De La Ville et al. (2002), Jayatissa et al. (2002), Kairo et al. (2002), Sulong et al. (2002) and Verheyden et al. (2002) provided remote sensing studies relevant to the field of sustainable development in tropical developing countries. Using these case-studies as examples of current remote sensing applications, this paper showed how remote sensing and GIS can be applied, developed and integrated in a sustainability framework to fulfil the local and global aims and needs stated above. It has been illustrated how air- and space-borne very high resolution imagery can help in identifying species or areas from a fundamental point of view (Sulong et al., 2002; Verheyden et al., 2002; Calzadilla Pérez et al., 2002), or for indicating the prioritary importance for protection and conservation (Dahdouh-Guebas et al., 2002b; Jayatissa et al., 2002; Sulong et al., 2002), for development (De La Villa et al., 2002), or for sustainable exploitation (Dahdouh-Guebas et al., 2002b; Kairo et al., 2002). It should be emphasised that next to technological innovation and multidisciplinary integration there is also a need for fundamental understanding of the biocomplexity (including human factors) of tropical coastal ecosystems.

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